EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 21, 737–747 (1996)

USING A COMBINED SLOPE HYDROLOGY/STABILITY MODEL TO IDENTIFY SUITABLE CONDITIONS FOR LANDSLIDE PREVENTION BY VEGETATION IN THE HUMID TROPICS

A. J. C. COLLISON

Department of Geography, King's College London, Strand, London WC2R 2LS, UK

AND

M. G. ANDERSON

Department of Geography, University of Bristol, University Road, Bristol BS8 1SS, UK

Received 3 February 1995
Revised 14 March 1995

ABSTRACT

The susceptibility of cut slopes to landsliding can be reduced in certain circumstances by the establishment of a vegetation cover. However, the hydrological implications of allowing a cover to develop may offset the mechanical benefits of soil reinforcement by roots. The balance between hydrological and mechanical effects is critical on slopes which are susceptible to the development of an infiltration-induced transitory perched water table, a common cause of landslides in deep, tropical residual soils. This balance is likely to change both between slopes of different types as well as temporally on any given slope. The net effect of a vegetation cover must be predicted either before natural vegetation covers are allowed to encroach on bare slopes, or if engineers are considering the use of trees as a protective measure. This paper presents a method of calculating the impact of a vegetation cover on slope stability. Simulations carried out on a wide range of slope types suggest that where failure is most likely to be triggered by infiltration rather than ground water rise, large-scale vegetation covers may contribute to instability. Whether vegetation had a positive or negative impact on slope stability was controlled by the permeability of the soil matrix, whilst the magnitude of impact was controlled by the soil strength and the slope height.

KEY WORDS slope stability; modelling; vegetation; humid tropics

INTRODUCTION

The systematic use of vegetation covers in slope stabilization has been carried out for many centuries, with documentation on dam stabilization in China dating back to the 16th century (Lee, 1985). Biotechnical slope stabilization was put on a more scientific basis with the work of Endo and Tsuruta (1969), Gray (1974), Wu *et al.* (1979) and Waldron and Dakessian (1981) who identified a series of empirical and physically based relationships between root development and soil strength. In the past five years there has been increasing interest in the use of biotechnical approaches within conventional civil engineering, and a number of schemes are currently underway.

Biotechnical stabilization programmes have been undertaken in Nepal (Howell *et al.*, 1991), Malaysia (Bayfield *et al.*, 1992), Hong Kong (Greenway, 1987) and elsewhere throughout the humid tropics. Whilst much of this work is proving to be successful, most of the models used to estimate the impact of vegetation on slope stability in the humid tropics were developed in the temperature maritime regions of Alaska and the northwestern USA (see for example Gray (1970, 1978) and Brown and Sheu (1975). Transposition of these techniques to the more hydrologically complex environment of the humid tropics poses problems for geotechnical engineers and engineering geomorphologists, and may lead to the adoption of inappropriate

CCC 0197–9337/96/080737–11

vegetation covers. This paper examines some of the limitations in current practices, and presents an alternative approach using an adapted version of the distributed slope hydrology and stability model developed by Anderson and Lloyd (1991). The new scheme incorporates the major mechanical and hydrological effects of vegetation relevant to slope stability in a humid tropical environment. Using this model structure, a series of applications have been carried out to assess the complex stability responses to using vegetation on slopes.

LIMITATIONS IN CURRENT METHODS OF INCORPORATING VEGETATION INTO SLOPE STABILITY ASSESSMENTS

The field of biotechnical stabilization has its origins in studies of deforestation and the associated landsliding in the temperate maritime hillslope environments of northwest America. Previous studies have divided the effects of vegetation into those which change slope mechanical properties and those which change slope hydrology. The principal mechanical effects are soil strength reinforcement and increased normal load on a potential shear surface. The main hydrological effects are reduced effective precipitation reaching the ground, increased infiltration capacity and soil permeability and a net reduction in moisture content and the height of the water table (see Table I).

Distinction can be made between the temperate and the humid tropical environments as far as evaluating the impact of vegetation on the slope factor of safety (FOS). In the former case, subsoils are generally thin, enabling tree roots to penetrate the entire profile. Worst-case conditions generally involve complete saturation of the soil, removing the need for sophisticated assessments of the impact of vegetation on hillslope hydrology. On rectilinear slopes it may be reasonable to calculate the effect of tree cover using the infinite slope method of stability analysis. Numerous case studies using this approach have shown that tree cover increases the stability of a wide range of slope types (see for example Burroughs and Thomas (1976); Riestenberg and Sovonick-Dunford (1983); Ziemer and Swanston (1977)). The weight of evidence from such studies is such that it is almost universally accepted that vegetation has a favourable effect on slope stability.

However, in a humid tropical environment soil profiles can be much deeper, reaching depths of up to 30 m. Such deep soil profiles have two implications in respect of attempts to assess the effect of vegetation on slope stability. Firstly, roots are unlikely to occupy the entire profile, enabling a potential shear surface to pass beneath the root zone, avoiding the area of mechanically reinforced soil except where it emerges at the crest and toe of the slope. Secondly, landslides in deep soils may be initiated by the development of a perched water table during an intense rainstorm, rather than by a rise in the ground water table. This process is particularly important where slope stability is only maintained at high suctions, as it often the case in humid tropical environments (Ching *et al.* 1984). Since the location and extent of any change in pore pressure will critically affect stability, dynamic consideration of soil hydrology and the hydrological impact of vegetation is necessary. In particular it is necessary to evaluate the possibility that vegetation may lead to increased pore water pressures through greater infiltration capacity. This raises the possibility that in the humid tropics at least, the net balance between the mechanical and hydrological effects of vegetation may

Table I. The effects of vegetation on mass stability (adapted from Greenway, 1987)

Hydrological process	Impact on stability	Mechanical process	Impact on stability
Canopy interception	−	Increased surcharge	+/−
Canopy runoff (the 'thatch effect')	−	Canopy transmits wind dynamic forces into soil	−
Transpiration	−	Surface binding	+
Infiltration capacity	+	Root reinforcement	+
Soil permeability	+	Root buttressing	+

* −, Detrimental to stability; +, beneficial to stability

be detrimental rather than beneficial in certain situations. Current methods of stability assessment developed in temperate environments are not suitable for evaluating such process balances, a disturbing situation given the widespread use of bioengineering approaches in the tropics. There is therefore a need for a method of identifying those slope conditions in which vegetation will have a beneficial effect, and those where the net effect of vegetation may be detrimental.

THE MODELLING APPROACH

The core model used in this study is the combined hydrology/stability model (CHASM) developed by Anderson and Lloyd (1991). This model uses a two-dimensional finite difference hillslope hydrology model to predict transient pore pressures. The finite difference model employs Darcy's law, with unsaturated hydraulic conductivity being derived by the Millington Quirk method (Millington and Quirk, 1959). The lower model boundary condition is generally set to the hydraulic conductivity of the bottom cell (assuming deep percolation), although it can be set to bedrock permeability if known. In the situation of infiltration-induced failure the model is generally insensitive to this parameter. The pore pressure data (positive or negative) are incorporated into a stability model using Bishop's method to yield a FOS (Bishop, 1955). The model contains a search routine to locate the shear surface with the lowest FOS at each selected model time step. At the end of the simulation period the lowest FOS is identified, along with data on the shear surface location and pore pressure distribution. It is possible to run the model using stochastically generated input data to allow for the effects of field sampling uncertainty. In this case the model generates a probability of failure, rather than a deterministic FOS. The model has been validated in two exercises in Hong Kong and Malaysia, described in Collison *et al.* (1995).

The core model has been adapted to incorporate the effects of vegetation, namely: canopy interception, canopy-generated runoff, increased infiltration capacity, increased conductivity, increased soil strength. The governing equations and model structure are shown in Figure 1.

Canopy interception (loss of available precipitation due to evaporation from the canopy) is calculated by a subroutine which incorporates the following parameters: canopy area per cell (m^2/m^{-2}), leaf area index ratio (m^2/m^{-2}), maximum depth of canopy store (m), stemflow rate (per cent rainfall), maximum evaporation rate ($m\,s^{-1}$). Rainfall is stored in the canopy up to a maximum specified depth, beyond which throughfall occurs. Stored rain is subject to evaporation, determined by a sine-derived function based on time of day. In addition to throughfall, rain reaches the ground by stemflow at a rate determined by field data from the tropics (Herwitz, 1985). In addition to evaporation losses, canopy-generated runoff may occur when long grass is flattened by intense rain, forming a semipermeable thatch cover. This is incorporated into the model where appropriate by the use of shedding factors determined on field plots in Hong Kong (Lam and Premchitt, 1990). Shedding factor curves show the proportion of rainfall which will run off the canopy in rainstorms of varying size. A shedding factor can be set for each surface cell of the hydrology model where long grass is present, reducing effective rainfall by the appropriate amount.

Increased permeability due to roots was measured using the assumption that most additional flow will occur down non-capillary macropores (pores with a diameter greater than 0·3 mm). Such voids are likely to be caused by diurnal fluctuations in the diameter of roots due to plant respiration (Huck *et al.*, 1970). Macropore flow was measured for a number of vegetated sites using a controlled head infiltrometer similar to that used by Topp and Zebchuck (1985). Using this technique infiltration is measured initially throughout the entire soil sample and then through the matrix only, the difference between the two measurements being the infiltration capacity of the macropores. Application of the method on root-permeated soil proved difficult since radial root patterns frequently made placement of the infiltration ring almost impossible. As a result, insufficient data were gathered to produce any statistically reliable relationships, but a general increase in macropore infiltration capacity with increasing root density was noted. Based on an average root density of 0·1 per cent ($10\,cm^2\,m^{-2}$), this gave an increase in permeability of $2{\cdot}3 \times 10^{-6 m s^{-1}}$ due to the presence of roots.

Roots increase soil strength by providing direct resistance to shearing and by mobilizing shear strength over a wider area through the transmission of tangential shear forces between roots and soil. Several models

exist which enable predictions of increased shear strength to be made, notably those developed by Wu *et al.* (1979) and Waldron and Dakessian (1981). Although approaching the problem with varying degrees of complexity, the models of Wu and Waldron were found by Gray (1978) to produce similar estimations of soil strength. Wu's model calculates increased soil strength from the root area ratio at the shear surface:

$$c = 1{\cdot}2(Tr \times RAR) \tag{1}$$

where c = increased soil cohesion (KPa), Tr = root tensile strength (KPa), RAR = root area ratio.

Since the model developed in this paper permits the incorporation of soil layers with different strength and hydrological properties, complex patterns such as individual root balls can be modelled, rather than the simplified homogeneous root zones assumed by existing bioengineering models (e.g. Gray and Brenner, 1970). Additional soil strength due to roots is incorporated directly into the Mohr Coulomb soil strength equation as increased effective cohesion (KPa), whilst additional permeability is simply added to the matrix permeability.

The resulting model has been tested, and a sensitivity analysis carried out to identify the key inputs (Anderson and Kemp, 1991; Collison *et al.*, 1995). In a comparative analysis of a group of failed slopes the model simulations successfully predicted 66 per cent of failures in Hong Kong and 75 per cent of failures in Malaysia. This compares with a success rate of approximately 50 per cent when using conventional stability monograms. The most important vegetation-related parameters are cohesion, canopy loss (thatch effect) and permeability. Parameters related to canopy interception and evaporation (canopy area, leaf area

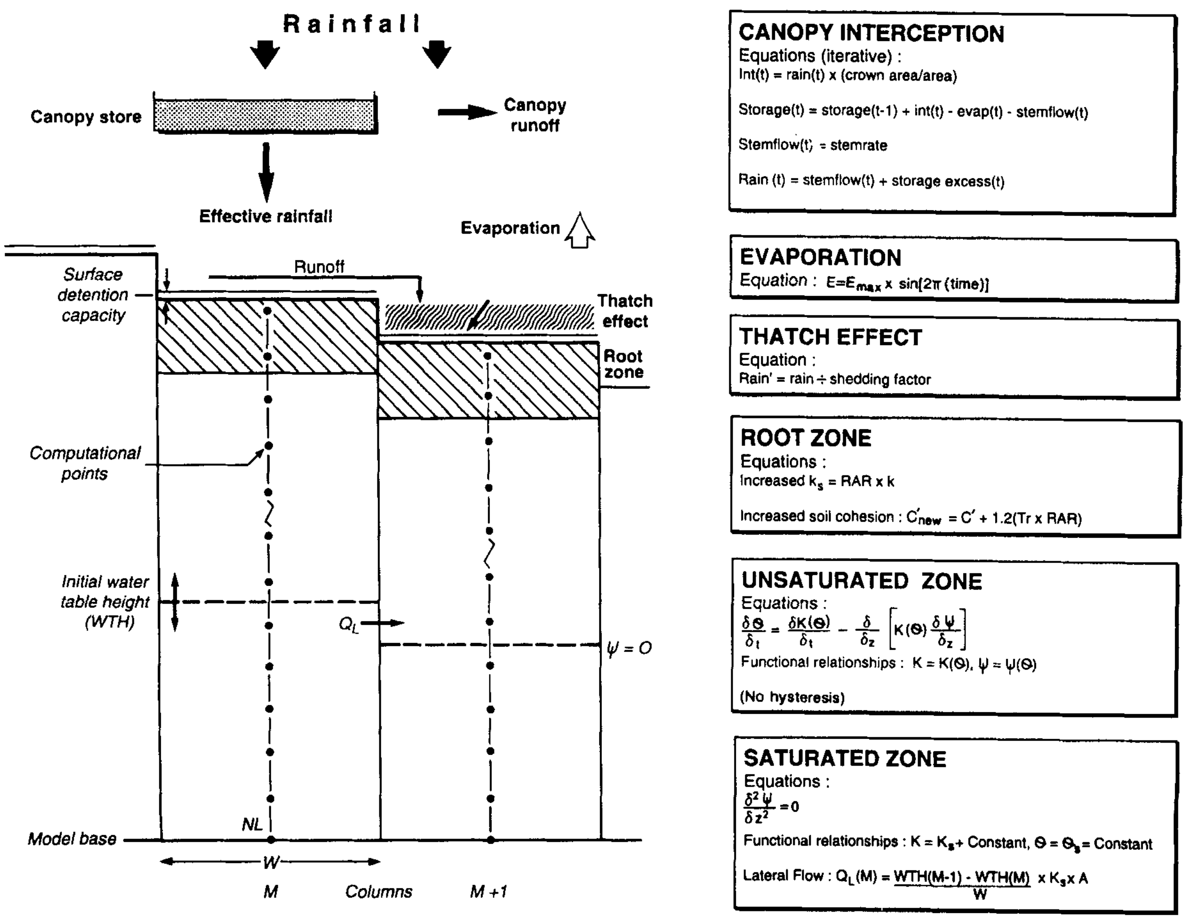


Figure 1. Structure of the vegetation slope cover model (z is height above datum (model base); Θ is volumetric water content; for definitions of other terms see figure or text)

Ksat	c phi	6 m	12 m	18 m	24 m	30 m	36 m
1×10^{-7} m/sec	0 30	1.33	1.07	0.98	0.95	0.93	0.92
	5 35	2.00	1.51	1.34	1.25	1.23	1.21
	10 35	2.36	1.72	1.49	1.37	1.33	1.29
1×10^{-6} m/sec	0 30	1.325	1.02	0.95	0.91	0.93	0.92
	5 35	1.80	1.45	1.30	1.22	1.22	1.21
	10 35	2.17	1.66	1.45	1.33	1.32	1.28
1×10^{-5} m/sec	0 30	1.325	0.93	0.87	0.87	0.90	0.90
	5 35	1.72	1.36	1.25	1.17	1.19	1.18
	10 35	2.09	1.58	1.40	1.28	1.28	1.26

Figure 2. Matrix of soil parameters and FOS values for non-vegetated slopes

index, maximum canopy depth, evaporation rate and stemflow rate) were found to have little effect on slope FOS in high intensity rainstorms.

IDENTIFYING THE OPTIMAL SLOPE CONDITIONS FOR LANDSLIDE PREVENTION BY VEGETATION

Three trial applications of the model have been carried out in order to assess the degree to which vegetation effects are variable depending upon slope conditions and spatial configuration. The first involved the simulation of different types of slope along the Kuala Lumpur to Karak highway, West Malaysia, to identify the influence of vegetation on slope conditions. Using site investigation data gathered during the highway construction, slopes were categorized into 54 types covering the known range of height (6–36 m), permeability (1×10^{-7} to 1×10^{-5} m s^{-1}) and soil strength combinations. All slopes simulated were at 45 degree slopes, the standard angle for cut slopes in this area. Figure 2 shows the matrix of soil parameter assumptions used and the FOS for non-vegetated slopes. For the initial investigation a design precipitation event of 265 mm in 24 hours was used, such an event having a return frequency of 100 years. Such an event falls within the design criteria for construction work in the humid tropics (see Geotechnical Control Office, 1984), and was deemed to be suitable to identify the significance of hydrological parameters within this scheme.

The model was used to examine the resultant sensitivity of FOS on each of the 54 slope types to a range of complete vegetation covers (see Table II), so as to identify those slopes which had the potential to be made more stable by vegetation covers. Sensitivity was determined in two stages: identification of critical slopes, followed by sensitivity assessment. Initially, slopes were simulated with each vegetation type to calculate the change in FOS, the greatest positive (Figure 3a) and negative (Figure 3b) change in FOS being noted. Of the 54 slope types, 11 had a FOS of at least 1·4 regardless of the cover, and were defined as non-critical (i.e. not needing further stabilizing measures, and not likely to be destabilized by vegetation). These were small slopes (6–18 m in height) with high soil strengths. Of the remaining slope types, 18 displayed a change in FOS of greater than 0·1, which was used as a threshold value denoting sensitivity to vegetation.

Table II. Vegetation modifications to the soil system

Vegetation	Cohesion (kPa)	Saturated conductivity (m s^{-1})
Grass	0	$+2{\cdot}3 \times 10^{-6}$
Shrub	+4	$+2{\cdot}3 \times 10^{-6}$
Tree	+14	$+2{\cdot}3 \times 10^{-6}$

The results of this assessment indicate that for the conditions assessed in this study the impact of vegetation can be significant. These effects are summarized in Figure 4. Three processes can be observed. The soil matrix permeability determines whether vegetation has a beneficial or detrimental effect on slope stability. Where the change in permeability due to vegetation is slight compared with the matrix permeability, the

(a)

Maximum *positive* effects of vegetation on the slopes simulated

Ksat	c phi	6m	12m	18m	24m	30m	36m
1 x 10^{-7} m/sec	0 30	0	0	0	0	0	0
	5 35	0	0	0	0	0	0
	10 35	0	0	0	0	0	0
1 x 10^{-6} m/sec	0 30	0.04	0	0	0	0	0
	5 35	0.03	0	0	0	0	0
	10 35	0	0	0	0	0	0
1 x 10^{-5} m/sec	0.285	0.24	0.11	0.08	0.04	0.03	0.02
	5 35	0.22	0.11	0.06	0.04	0.03	0.03
	10 35	0.20	0.10	0.05	0.04	0.03	0.01

Non-critical Slopes   0.08 *Maximum Positive Effect*

(b)

Maximum *negative* effects of vegetation on the slopes simulated

Ksat	c phi	6m	12m	18m	24m	30m	36m
1 x 10^{-7} m/sec	0 30	0.67	0.66	0.59	0.56	0.01	0.01
	5 35	0.56	0.37	0.23	0.15	0.01	0.01
	10 35	0.43	0.21	0.08	0.05	0.01	0.01
1 x 10^{-6} m/sec	0 30	0.51	0.61	0.54	0.53	0.10	0.01
	5 35	0.32	0.33	0.21	0.13	0.02	0.01
	10 35	0.18	0.10	0.05	0.03	0.01	0.01
1 x 10^{-5} m/sec	0.285	0.24	0.11	0	0	0	0
	5 35	0.18	0	0	0	0	0
	10 35	0	0	0	0	0	0

Non-critical Slopes   0.08 *Maximum Positive Effect*

Figure 3. FOS changes for vegetation types (Table II) and slope conditions (Figure 2) showing (a) maximum positive effects and (b) maximum negative effects of vegetation

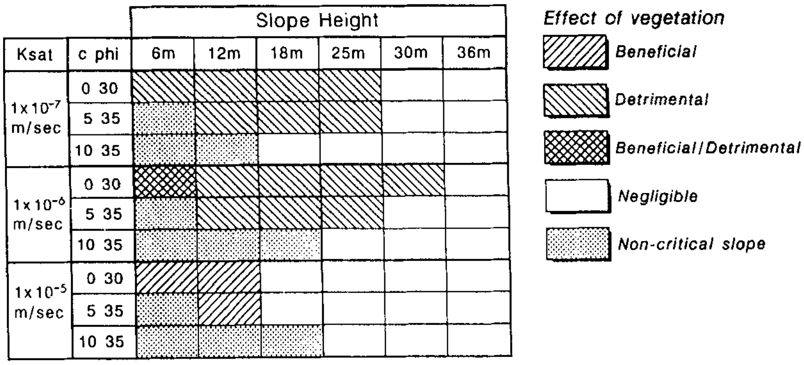


Figure 4. Summary of change in FOS due to vegetation for a sample of type-slopes on the Kuala Lumpur to Karak Highway, Malaysia, showing the controlling influence of slope height, soil permeability and strength (being a composite of Figures 3a and 3b)

impact of vegetation tends to be beneficial. Where the converse situation exists the impact is detrimental, implying that the permeability discontinuity at the base of the root zone causes increased pore pressures to develop. This is illustrated by Figure 5 which shows the distribution of pore pressures for a 6 m slope with and without a tree cover. The magnitude of influence vegetation exerts on stability is controlled by soil strength and slope height. High soil strengths simply reduce the relative impact in FOS due to vegetation. The influence of slope height is more complex. Increasing height reduces the impact of vegetation, but the degree to which this occurs is different for the hydrological and mechanical effects of vegetation. The hydrological (generally negative) effects of vegetation are observed on slopes up to 24 m, whilst the mechanical (beneficial) effects become negligible at slope heights of around 18 m.

The pattern described above arises for two reasons. Firstly, on slopes with strong roots the shear surfaces were found to pass mostly beneath the root zone, penetrating it only at the head and toe of the failure. On small slopes this still brings about mechanical benefits from vegetation since the distance of root zone which the shear surface has to pass through is a significant proportion of the total shear surface length. On large slopes, however, the proportion of the root zone which has to be penetrated is smaller, and the degree of displacement less significant, making the mechanical benefit negligible. However, although the mechanical effects of vegetation are reduced as the shear surface becomes deeper, the hydrological impact of vegetation

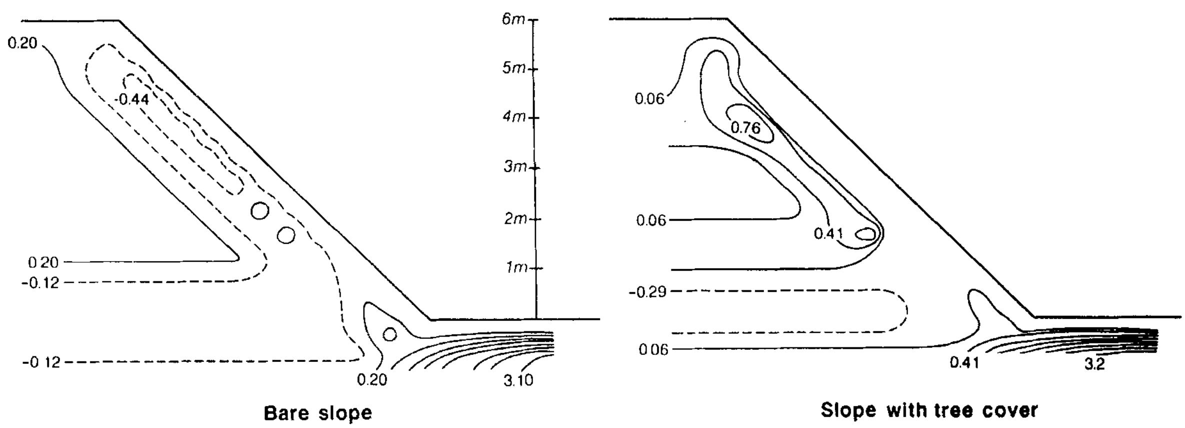


Figure 5. Difference in pore pressure distribution for vegetated and non-vegetated slopes with a saturated permeability of $1 \times 10^{-6}\,m\,s^{-1}$

is felt well below the root zone, shifting the process in favour of the hydrological properties of vegetation. The net effect is that with increasing slope height vegetation has less effect, and the effect is more likely to be negative. The slopes which have the potential for biotechnical stabilization on the Kuala Lumpur to Karak highway are therefore those which have relatively permeable soils (1×10^{-6} to $1 \times 10^{-5}\,m\,s^{-1}$) and a vertical elevation less than 18 m. Slopes which are higher than 18 m are relatively unaffected by vegetation and are best protected either by a long grass cover, which reduces available rainfall whilst reducing erosion, or by an impermeable synthetic cover such as gunite. These general observations can be seen by reference to Figure 4. Whilst it can be construed that on the higher slopes vegetation might help prevent shallow slides, it is the deeper slides on such slopes that are critical failures, as determined by the stability search procedure employed in the combined model developed here.

IDENTIFYING THE OPTIMAL VEGETATION CONFIGURATION FOR SLOPE STABILIZATION

The complex range of responses to vegetation indicates that simple, complete slope covers may not be the most favourable remedial measure for those slopes where vegetation has a generally beneficial impact. In order to assess this assertion a number of slopes with potential for biotechnical stabilization were simulated in more detail to establish the effect of tree location on slope stability. An example of the analysis is shown in Figure 6. Slopes were simulated with tree covers on the toe, crest, toe and crest, slope face and entire slope. The simulations illustrate the importance of the spatial distribution of vegetation in determining whether or not a remedial vegetation cover will have a favourable impact on stability. Of the slopes with bioengineering potential, those with a height of 6 m were found to benefit from a complete tree cover. Higher slopes were found to benefit most from tree cover on the toe at the point where the shear surface is most likely to emerge, with long grass above this to reduce on-slope infiltration. Toe reinforcement was found to displace the shear surface either deep beneath the surface (avoiding the zone of high pore pressures) or high on the slope face where the gradient of the surface was reduced, increasing normal stress and so shearing strength. Tree planting on the toe was found to combine mechanical reinforcement with minimal hydrological impact.

IDENTIFYING THE TIME TAKEN TO ACHIEVE STABILIZATION USING A VEGETATION COVER

The applications described above assume complete vegetation cover at the time of the precipitation event. However, in the case of a cut slope, full tree establishment could take up to 20 years. During this period an extreme rainfall event could cause failure, particularly if a partial cover results in a lower FOS. Viability of bioengineering schemes will depend not just on the eventual potential increase in FOS, but, crucially, on the time taken to achieve stability and the FOS during this period. To assess the viability of establishing a tree cover on a slope, two sets of simulations were carried out on slopes which the sensitivity test had indicated would gain from a full tree cover. The first assessments simulated cover development on a 6 m slope with a permeability of $1 \times 10^{-5}\,m\,s^{-1}$, the second with a permeability of $1 \times 10^{-6}\,m\,s^{-1}$. A simple model of tree growth was used to estimate the extent of the canopy and root ball for acacia saplings over time. This assumed an asymptotic growth rate based on the following formula:

$$dt = dt - 1\left[1 + g\frac{(1 - dt - 1]}{D}\right] \tag{2}$$

where dt = diameter (m) at current time increment, $dt - 1$ = diameter (m) at previous time increment, g = growth rate function, and D = maximum diameter attainable (m).

Each slope was simulated at five yearly growth intervals with the 100 year return frequency storm. Although both slopes eventually benefit from a full cover, the medium-term responses of the two slopes are markedly different, as illustrated in Figures 7a and 7b. The more permeable slope is not detrimentally

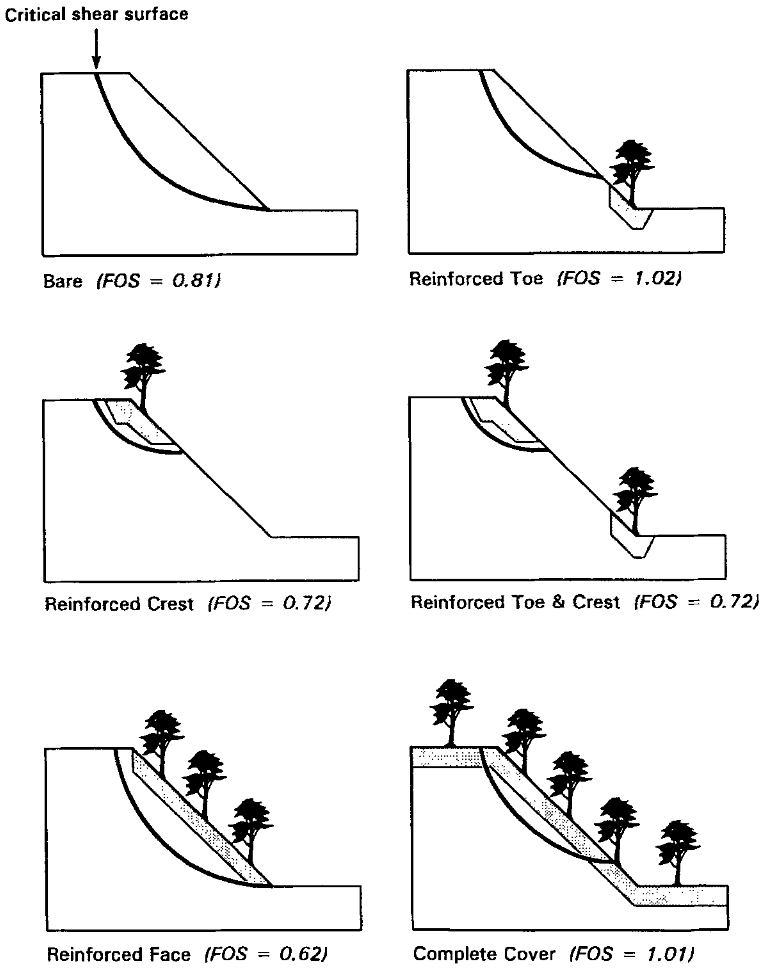
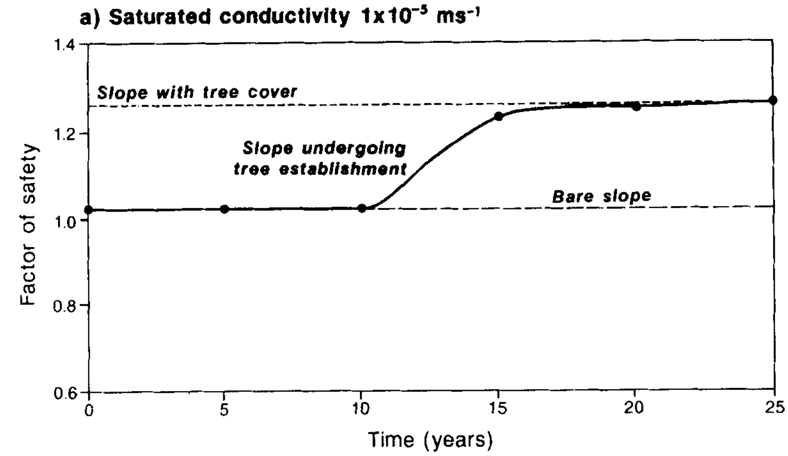


Figure 6. The effect of vegetation distribution on FOS of a 12 m high slope with a saturated conductivity of 1×10^{-6} m s^{-1}. Shaded areas indicate extent of the vegetated zone modelled using the canopy and root zone equations given in Figure 1

affected by the increase in permeability associated with tree development, and undergoes a gradual increase in FOS. On the less permeable slope the trees cause a sharp conductivity differential at the edge of the root zone, enabling high pore water pressures to develop. Stability analysis shows that the shear surface passes through the zone of high pore pressure beneath the root zone. The FOS is thus less than that of a bare slope until the root balls coalesce after 20 years. It is only then that the shear surface passes through the reinforced zone.

CONCLUSIONS

The viability of a bioengineering scheme can be quantitatively assessed using the model described in this paper. Given the time taken to achieve maximum stability, it is possible to calculate the risk of failure occurring during the establishment of vegetation. For example, in the case of the 6 m slopes cited above, the time taken to reach the maximum benefit of vegetation-induced stability enhancement is 20 years. The model can then be used to predict the effect of a series of events with given return intervals on the incomplete slope cover during the vegetation enhancement period. The resulting curves can be used to calculate the cumulative probability of failure for the bare slope, and for the same slope with a bioengineering scheme. This quantifies both the risk and the benefit of a particular solution, and may indicate the need for interim conventional engineering measures such as geotextiles before the desired level of stability is achieved naturally. The viability



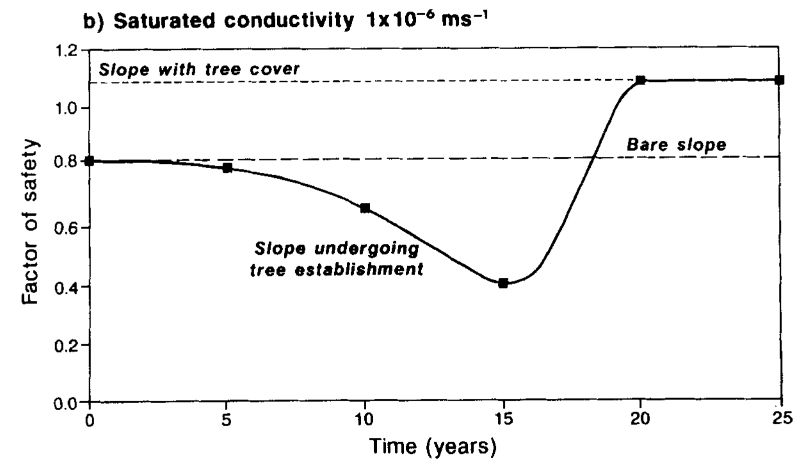


Figure 7. (a) Change in FOS over time for a high permeability ($1 \times 10^{-5}\,m\,s^{-1}$) slope undergoing remedial biotechnical stabilization. (b) Change in FOS over time for a medium permeability ($1 \times 10^{-6}\,m\,s^{-1}$) slope undergoing remedial biotechnical stabilization

of alternative planting strategies such as inter-planting can also be assessed. Though the method is quantitative it is not objective since the criteria will vary depending upon the purpose of the bioengineering scheme. For example, if a bioengineering scheme is intended to offset an eventual decline in stability due to de-consolidation, a medium-term decline in FOS may be acceptable. If the scheme is intended to protect an already vulnerable slope any intermediate decline in FOS will not be acceptable.

This paper has outlined a model which enables the quantitative evaluation of the effectiveness of vegetation covers planted to prevent shallow, infiltration-induced failures in the tropics. The scheme incorporates a number of advantages over existing bioengineering methods. A wider range of vegetation-influenced slope properties are considered, extending the scope of model application. In particular, incorporation of the hydrological effects of vegetation makes the model better suited for use in the tropics, where many slope failures are caused by infiltration-induced pore pressure change rather than by rises in the ground water table. The dynamic nature of the model enables potential vegetation covers to be appraised under rainstorms of different return frequency, allowing designers to determine the probable design life of particular cover combinations. The model also permits both spatial and temporal changes in vegetation cover to be analysed, enabling evaluation of both the ideal configuration of the cover and the time taken to achieve target levels of stabilization.

ACKNOWLEDGEMENTS

The work reported in this paper was funded by the Transport Research Laboratory, UK. The authors acknowledge the assistance of the Malaysian Public Works Department (IKRAM) in providing field and laboratory support.

REFERENCES

Anderson, M. G. and Lloyd, D. M. 1991. 'Using a combined slope hydrology–stability model to develop cut slope design charts', *Proceedings of the Inst of Civil Engineers*, **91**, 705–718.

Bayfield, N. G., Barker, D. H. and Yah, K. C. 1992. 'Erosion of road cuttings and the use of bioengineering to improve slope stability in Peninsular Malaysia', *Singapore Journal of Tropical Geography*, **13**(2), 75–89.

Bishop, A. W. 1955. 'The use of the slip circle in the stability analysis of slopes', *Geotechnique*, **5**, 7–17.

Brown, C. B. and Sheu, M. S. 1975. 'Effects of deforestation on slopes', *Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers*, **26**(101), 147–165.

Burroughs, E. P. and Thomas, R. R. 1976. *Root strength of Douglas fir as a factor in slope stability*, USDA Forest Service Review, draft INT 1600–12 (9/66).

Ching, R. K. H., Sweeney, D. J. and Fredlund, D. G. 1984. 'Increase in factor of safety due to soil suction for two Hong Kong slopes', *Proceedings 4th International Symposium on Landslides*, Toronto, Canada, September 1984, **1**, 617–623.

Collison, A. J. C., Anderson, M. G. and Lloyd, D. M. (1995). 'The impact of vegetation on slope stability in a humid tropical environment—a modelling approach', *Institution of Civil Engineers, Water, Maritime and Energy*, **112**, 168–175.

Endo, T. and Tsuruta, T. 1969. 'The effect of tree roots upon the shearing strength of soil', *Annual Report Of The Hokkaido Branch, Tokyo Forest Experimental Station*, **18**, 167–182.

Geotechnical Control Office. 1984. *Geotechnical Manual For Slopes*, Hong Kong, GCO, 295pp.

Gray, D. H. 1970. 'Effects of forest clear-cutting on the stability of natural slopes', *Association of Engineering Geologists Bulletin*, **8**, 45–67.

Gray, D. H. 1974. 'Reinforcement and stabilisation of soil by vegetation'. *Journal of Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers*, **100**, 695–699.

Gray, D. H. 1978. 'Role of woody vegetation in reinforcing soils and stabilising slopes', *Symposium on Soil Reinforcing and Stabilising Techniques*, Sydney, Australia, 1978, 253–306.

Gray, D. H. and Brenner, R. P. 1970. 'The hydrology and stability of cutover slopes', *Proceedings of the Conference on Interdisciplinary Aspects of Watershed Management*, American Society of Civil Engineers, 295–326.

Greenway, D. R. 1987. 'Vegetation and slope stability', in Anderson, M. G. and Richards, K. S. (Eds), *Slope Stability*, John Wiley and Sons, Chichester, 187–230.

Herwitz, S. R. 1985. 'Interception storage capacities of tropical rainforest canopy trees', *Journal of Hydrology*, **77**, 237–252.

Howell, J. H., Clark, J., Lawrence, C. and Sunwar, I. 1991. *Vegetation Structures for Stabilising Highway Slopes: a Manual for Nepal*, UK/Nepal Eastern Region Interim Report of the Maintenance and Rehabilitation Coordinating Unit, Dept of Roads, Babar Mahal, Kathmandu.

Huck, M. G., Klepper, B. and Taylor, H. M. 1970. 'Diurnal variations in root diameter', *Plant Physiology*, **45**, 529–530.

Lam, T. S. K. and Premchit, J. 1990. *Rainstorm-runoff on Slopes 1984–88*, Civil Engineering Services Reprt Hong Kong, Special Project Report 1 1/90.

Lee, I. W. Y. 1985. 'A review of vegetative slope stabilisation', *Journal of the Hong Kong Institute of Engineers*, 9–21.

Millington, R. J. and Quirk, J. P. 1959. 'Permeability of porous media', *Nature*, **183**, 387–388.

Riestenberg, M. M. and Sovonick-Dunford, S. 1983. 'The role of woody vegetation on slope stability in the Cincinnati area, Ohio, *Geological Society of America Bulletin*, **94**, 506–518.

Topp, G. C. and Zebchuck, W. D. 1985. 'A closed adjustable head infiltrometer, *Canadian Agriculture Engineering*, **27**, 99–104.

Waldron, L. J. and Dakessian, S. 1981. 'Soil reinforcement by roots: calculation of increased soil shear resistance from root properties', *Soil Science*, **132**(6), 427–435.

Wu, T. H., McKinnel, W. P. and Swanston, D. N. 1979. 'Strength of tree roots and landslides on Prince of Wales Island, Alaska', *Canadian Geotechnical Journal*, **16**, 1933.

Ziemer, R. R. and Swanston, D. N. 1977. *Root Strength Change after Logging in Southeast Alaska*', USDA Forest Service Research Note, PNW-306.